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THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

J. H. L. VOGT
Trondhjem, Norway

III

ON THE QUARTZ, CRYSTALLIZING AT A LATE STAGE, IN QUARTZ- BEARING NORITES, GABBROS, SYENITES, DIORITES, ETC.

In the rocks here mentioned, where the quantity of quartz does not surpass 5 per cent or occasionally—especially in some quartz-diorites¹—somewhat more, the quartz, as is well known, appears as *Zwischenklemmungsmasse*, or mesostasis, indicating a very late stage of crystallization. If we for convenience' sake only concern ourselves with the gabbroidic rocks, we find this depending on the fact that in a complicated system (Ab+An:ferromagnesian metasilicates [with other pyroxene components]:Qu), a great deal of plagioclase and pyroxene will crystallize at an early stage if the Qu component is present only in small quantity. By this means the quantity of the Qu component in the mother-liquid increases, and the quartz can only commence forming when a complicated eutectic boundary between Qu and Ab+An and ferromagnesian silicates has been reached.

In this manner the quartz will fill the intervening spaces between the already formed plagioclase and pyroxene individuals. At this late stage of crystallization, however, we have not, as occasionally assumed by some earlier investigators, a crystallization of quartz alone, but, on the contrary, of quartz simultaneously with some plagioclase and ferromagnesian silicate. The fact is that the quartz in the mesostasis often forms a pegmatitic or granophyric intergrowth as well with the plagioclase as with the pyroxene in

¹ Rocks with acid plagioclase, with at least 15 per cent quartz, I do not include in the group of diorites.

question. As an example we refer to Figures 17 and 18 of a quartz-norite from Erteli, Norway, consisting of about 60 per cent labradorite, 35 per cent hypersthene (with a little secondary hornblende), and on the average 5 per cent quartz, but without oxidic iron ore and without biotite. Some parts of the thin section show only $\frac{1}{2}$, 1, or 2 per cent of quartz, but locally, as in the part photographed, the quantity of quartz rises much higher, even to 20 per cent.

The relative proportions of the three minerals of the last stage of crystallization cannot be accurately defined under the microscope. We get the impression, however, that the percentage of

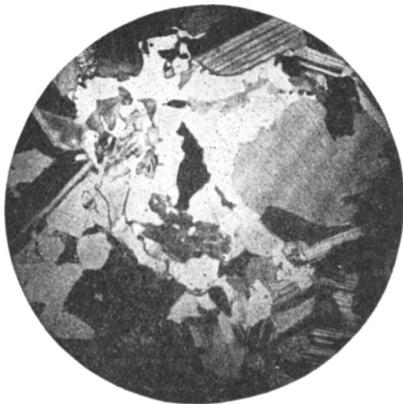


FIG. 17.—Photomicrograph between crossed nicols (24:1).

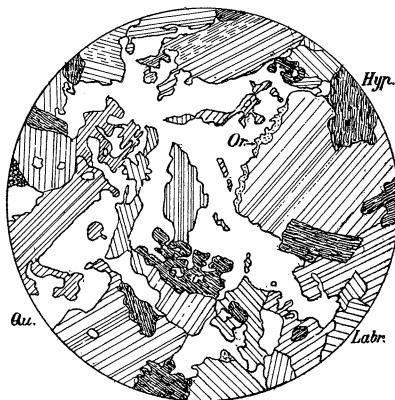


FIG. 18.—Drawing (27:1)

Hyperitic-structured quartz-norite from Erteli, Norway. Labradorite, with twinning lamellae after the albite law (and quite subordinate after the pericline law). Hypersthene (dark shading) with a little secondary hornblende. A little orthoclase (dotted in diagram) at the periphery of one or two labradorite individuals. The drawing represents about seven-eighths of the photomicrograph.

ferromagnesian silicates in the final product of the solidification is quite small. As an estimate we may rate about 55 per cent labradorite, 35 per cent quartz, and 10 per cent pyroxene.

Their mutual proportions, however, will to a great extent be dependent upon the composition of the plagioclase and the pyroxene.

Originating from the values mentioned, we may imagine a norite or gabbro with 3.5 per cent quartz, where the quartz and

the remaining part of the final product will commence to crystallize only after all in all 90 per cent plagioclase and pyroxene have solidified.

As is well known, a little orthoclase or microcline often appears with the quartz in the mesostasis of the gabbro rocks. The explanation of this fact is quite simple. If the magma contains somewhat more Or ($KAlSi_3O_8$) than is absorbed by the plagioclase, the small surplus of Or will be concentrated in the final magma, and consequently will crystallize together with the quartz and some plagioclase and ferromagnesian silicate in the mesostasis.

In the chapter in Part II on the "Oligoclase-Granite Dikes" of many gabbros and norites, we will show that these dikes represent the final magma, resulting at a very late stage of the crystallization of gabbroidic magmas which contain a little quartz.

ON THE DIFFERENCE BETWEEN THE SOLUBILITY OF THE FERROMAGNESIAN SILICATES IN ACID (GRANITIC) AND BASIC (GABBROIDIC) MAGMAS

We shall commence by mentioning some binary eutectics.

Synthetic determinations, according to the Geophysical Laboratory, Washington:

Qu (crystobalite, *ca.* 1650°):An (1550°) = 48 per cent Qu:52 per cent An (1353°).

Qu (crystobalite):Diops (1391.5°) = 16 per cent Qu:84 Diops (1362°).

An:Diops = 42 per cent An:58 per cent Diops (1270°).

Ab (*ca.* 1100°):Diops = about 97 per cent Ab:3 per cent Diops. (The last statement is according to extrapolation by Bowen.)

Analytical (see above) Qu:Ab = about 28 per cent Qu:72 per cent Ab.

For the Na_2O -rich granites containing pyroxene instead of the usual biotite we must assume that Qu:Ab:Diops (at high pressure) form a ternary eutectic. The same must be assumed also for Qu:An:Diops. The latter system, however, is of subordinate interest petrographically. For the ternary systems Qu:Ab:Diops and Qu:An:Diops, with regard to which we know all the binary eutectics between the individual substances, we shall construct the approximate ternary systems, Figure 19. We here especially fix our attention on the fact that the ternary eutectic Qu:Ab:Diops can contain no more than a few per cent, or probably not even so much, of diopside. On the other hand,

the eutectic boundary-line between diopside (or pyroxene in general) and anorthite, bytownite, and labradorite (see above) contains as much as about 55, 45, and 35 per cent pyroxene respectively, and these figures will only be displaced to a slight degree by the presence of a lesser quantity of quartz, as 2, 5, or 10 per cent.

In magmas of *granitic* composition, with Ab as the plagioclase, diopside must consequently commence crystallizing earlier than plagioclase (albite), even if only as little as a few per cent of diopside are present. In magmas of *gabbroodic* composition (with labra-

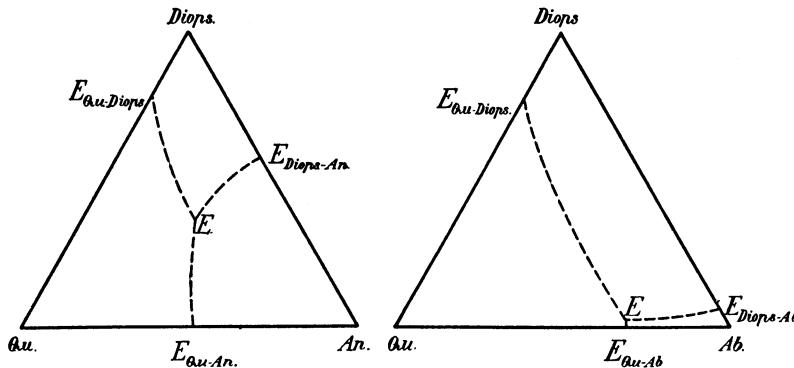


FIG. 19.—Diagrams of the individualization fields Qu:Diops:An, and Qu:Diops:Ab.

dorite or bytownite), on the other hand, plagioclase commences crystallizing earlier than the pyroxene, even if as much as 35–40 per cent of pyroxene is present.

This result with regard to the slight solubility of $\text{CaMgSi}_2\text{O}_6$ in acid magmas, deduced from physico-chemical foundations, is verified by the petrographical investigation of granitic igneous rocks. And this slight solubility in the acid igneous rocks Fe applies not only to diopside, but also to the Mg, Ca-, Mg, Fe, Ca-, or Mg, Fe-silicates in general.

It is apparent that—

1. The crystallization of the silicates in the granites (with about 70–76 per cent SiO_2) commences with the crystallization of the ferromagnesian silicates (biotite, hornblende, augite, hypersthene) when the latter is present in a quantity of at least a few

per cent. With more basic plagioclase (andesine) somewhat more of the ferromagnesian silicate must be present if the latter is to commence crystallizing earlier than the plagioclase.

2. In the granitic eutectic we only find a trifle MgO, viz., according to the analyses collocated on page 348, we find in magmas with little An only about 0.2 per cent MgO (and in the magmas, somewhat richer in An, possibly as much as about 0.5 per cent MgO).

The very great difference between the degree of solubility of ferromagnesian silicates (mica, pyroxene, or hornblende) in *acid* rocks, consisting chiefly of acid feldspar and quartz, and in *basic* rocks, containing basic plagioclase, is of great petrologic importance.

ORTHORHOMBIC AND MONOCLINIC PYROXENE

In orthorhombic pyroxene we often observe microscopically small lamellae of monoclinic pyroxene, and in monoclinic pyroxene corresponding minute lamellae of orthorhombic. This must (see above, p. 436) be explained as a secondary phenomenon, due to a secretion in the solid phase.

Where *independent* individuals of orthorhombic and monoclinic pyroxene are intergrown, the orthorhombic (hypersthene)—as has often been pointed out by earlier investigators and as I have often observed in norites containing diallage—forms the kernel and the monoclinic (diallage) the surrounding parts. This indicates that the hypersthene was formed earlier than the diallage. Exceptionally also we find large crystals of hypersthene, with quite good idiomorphic outlines, inclosed in the diallage.

We here refer to Figures 20–21 of a norite,¹ containing diallage, from Skjækerdalen in Norway, and consisting of about 5 per cent olivine (according to the determination of the optical character and the axial angle with 20–25 per cent Fe_2SiO_4) in scattered individuals (not represented in the section drawn); about 25 per cent hypersthene (according to optical determination with about 25 per cent FeSiO_3); about 25 per cent diallage (optically positive, $2V = ca. 65^\circ$, $c:c = ca. 43^\circ$) with a little primary brown hornblende;

¹ This rock has recently been treated by C. W. Carstens, *Geology of the Trondhjem District*, 1920, p. 101.

about 40 per cent labradorite (about Ab_2An_3); and about 5 per cent pyrrhotite. If we leave out of consideration the olivine, which appears only here and there and whose age we were unable to determine with certainty in the present case, the hypersthene is the oldest mineral, as it shows an idiomorphic contour against all the other minerals—however, with somewhat rounded edges. (See the remarks in a following chapter.)

We especially emphasize that crystals of hypersthene in several places have swum together to small aggregates, showing a synneusis structure (see the left side of Fig. 21), and that the hypersthene shows idiomorphic outlines also against the diallage, with



FIG. 20.—Photomicrograph (15:1)

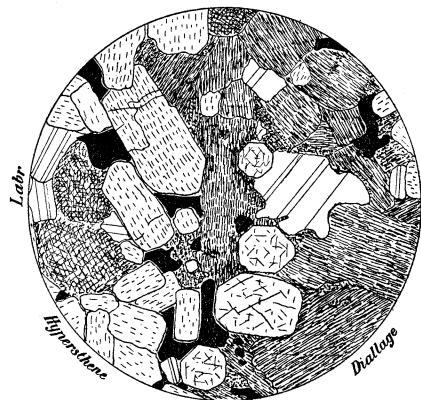


FIG. 21.—Drawing (15:1)

Norite from Skjækerdalen, Norway. Contains hypersthene (in the photograph light gray, in the drawing lightly shaded), diallage (in the photograph darker gray, in the drawing dark shading), and a little brown hornblende (dotted in diagram), labradorite (white in the photograph, showing twin lamellae in the drawing), and some pyrrhotite (black).

which, in the present case, it is not in parallel growth. This cannot be explained otherwise than that the hypersthene had finished forming before the commencement of crystallization of the diallage.

I believe I am right in drawing the conclusion that when hypersthene and diallage appear together in igneous rocks, the hypersthene, regardless of the quantitative proportion between the two minerals, is prevailingly the oldest. Hypersthene (consisting of two chief components) and diallage (consisting of several

components) are consequently related to each other as the components with high and low melting-points in the binary mix-crystal system No. IV (cf. Fig. 36).

PYROXENE AND BIOTITE, RESPECTIVELY HORNBLENDE, IN
THE GABBRO ROCKS

We have previously treated one case, viz., the quartz-norite from Romsaas (see pp. 434-35) where *hypersthene* first crystallized, but later stopped forming as the remainder of the ferromagnesian silicate in the magma entered into *biotite*. In another series of norites and gabbros with relatively much orthorhombic or monoclinic pyroxene and usually with only 2-5, seldom up to 8-10 per cent of biotite, we find the latter (see, for example, Fig. 13) partly grown into the *exterior* parts of, and partly grown on to, the pyroxene, indicating that the biotite belongs to a somewhat later stage of crystallization than the pyroxene.

Primary hornblende is lacking in numerous Norwegian norites and gabbros, but appears in others, most often, however, only in a quantity of 5-10 per cent. This primary hornblende, which always, or nearly always, is brown or greenish-brown, and probably throughout contains some titanic acid, often shows a parallel intergrowth with the orthorhombic or monoclinic pyroxene, in such a manner that the hornblende appears at the periphery of the pyroxene. Or the hornblende may have grown as independent individuals on to the pyroxene. This signifies also for the hornblende a stage of forming later than for the pyroxene. The explanation probably is that the original small contents of H_2O in the gabbroidic magma was concentrated in the residual magma by the solidification of a greater or lesser part of the pyroxene, so that biotite, respectively hornblende, was able to individualize. This will be discussed in a later chapter.

OLIVINE, Mg_2SiO_4 : Fe_2SiO_4

The melting-point of pure Mg_2SiO_4 , according to the determination at the Geophysical Laboratory, Washington, is 1890° . The melting-point of Fe_2SiO_4 lies, according to approximate determination, at *ca.* 1100° . Doelter gives *ca.* 1065° . Mg_2SiO_4 and Fe_2SiO_4 form a continuous mix-crystal series.

a) As there is such an exceedingly great difference between the melting-points of the two components, it must a priori be taken for granted that the binary system $Mg_2SiO_4:Fe_2SiO_4$ belongs to type I (without a maximum or minimum).

b) In zonal olivine we find, according to a number of investigators (Sigmund, Becke, Stark),¹ Mg_2SiO_4 concentrated in the

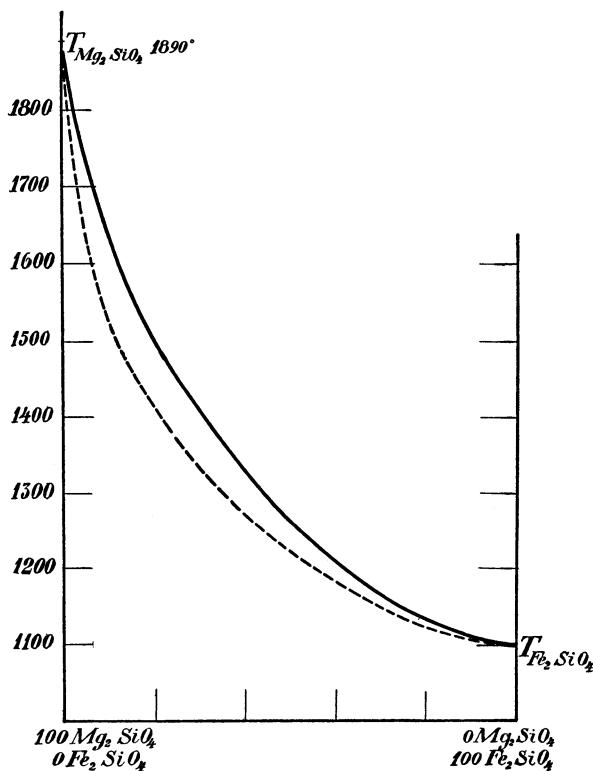


Fig. 22.—Schematic melting-diagram $Mg_2SiO_4:Fe_2SiO_4$ (percentages by weight)

kernel, and Fe_2SiO_4 in the peripheral zone. Stark found in a zonal olivine from basalt containing 19.5 per cent Fe_2SiO_4 in the kernel and 34.5 per cent in the exterior zone, consequently a marked difference, but not by far so great a difference as between Ab:An in the plagioclase of corresponding rocks. These investi-

¹ See *Tscherm. min. u. petr. Mitt.*, Vols. XVI, XVII, and XVIII.

gations of zonal olivine apply to the common rock-forming olivine, with at most 35–40 per cent Fe_2SiO_4 (and rest Mg_2SiO_4).

c) The earlier approximate determinations, especially by Doelter, show for olivine with increasing percentages of Fe_2SiO_4 , continuously decreasing "melting-points" (ɔ:melting-point interval).

d) The later investigations prove *inter alia* that even so small a percentage of Fe_2SiO_4 as 10–15 per cent lowers the melting-point interval of the olivine considerably below the melting-point of Mg_2SiO_4 . A maximum of the melting-curve, which in this case must have occurred at predominant Mg_2SiO_4 and little Fe_2SiO_4 , is therefore out of the question.

In conformity with all the above observations I believe myself justified in illustrating the binary system $\text{Mg}_2\text{SiO}_4:\text{Fe}_2\text{SiO}_4$ by the foregoing sketch (Fig. 22); it must be emphasized, however, that the course of the curve is only sketched.¹ As the zonal structure of the olivine is far less prominent and there is less difference between the two components than in the plagioclase in rocks with about the same cooling-rate, the difference between the liquidus and solidus curves must be less for $\text{Mg}_2\text{SiO}_4:\text{Fe}_2\text{SiO}_4$ than for An:Ab.

OLIVINE AND PLAGIOCLASE

As explained in my earlier treatise "Die Silikatschmelzlösungen," I and II (1903–4), olivine and anorthite do not crystallize at the pressure of one atmosphere in molten masses of certain intermediate mixtures of Mg_2SiO_4 and $\text{CaAl}_2\text{Si}_2\text{O}_6$, for here new minerals are formed, chiefly melilite and spinel. In conformity with this, in the treatise above cited, I discussed for basic silicate melts with anorthite and olivine as the two extremes, not the individualization boundary between olivine and anorthite, but between (a) olivine and melilite, and (b) melilite and anorthite.

O. Andersen (at that time with the Geophysical Laboratory, Washington), in his treatise "The System Anorthite:Forsterite:Silica,"² arrived at the same results, for by intermediate mixtures of An and Mg_2SiO_4 —viz., between 90 An:10 Mg_2SiO_4 and 54 An:46 Mg_2SiO_4 —he obtained crystallized spinel. At *high pressure*,

¹ A minimum in the neighborhood of Fe_2SiO_4 is not excluded but very improbable.

² *Loc. cit.*

as in the crystallization of deep-seated igneous rocks, we find a different case. *Forellengestein* or troktolite, for instance, consists of very basic plagioclase (anorthite-bytownite) and olivine. Some anorthosites show predominant plagioclase (bytownite, labradorite) and in addition some olivine, and some olivine gabbros consist chiefly of basic plagioclase and olivine with only a small amount of monoclinic or orthorhombic pyroxene. On remelting several of these rocks at atmospheric pressure, more or less melilite results, and in addition frequently some spinel, and occasionally also other minerals. At the pressure of one atmosphere, consequently, quite a different mineral combination results from the magmas here mentioned than the combination occurring in the deep-seated rocks. We shall in a following chapter discuss the cause of this. Here we shall only fix our attention on the fact that the melting of intermediate mixtures of $\text{CaAl}_2\text{Si}_2\text{O}_8$ and Mg_2SiO_4 at the pressure of one atmosphere does not give us the required information of the individualization boundary between plagioclase (anorthite) and olivine, which takes place at high pressure. In the question in hand, therefore, we must use the analytical method.

Petrographical experience shows that the olivine in most of the igneous rocks crystallized at a very early stage. Because of this fact, many petrographers have the conception that olivine takes an exceptional position with regard to the sequence of crystallization and that this mineral always crystallizes as No. I of the silicate minerals. This is, however, a misconception.¹ The reason why the olivine in numerous cases commences crystallizing earlier than the other silicates is that the individualization boundary between olivine and plagioclase or pyroxene, or between olivine and plagioclase plus olivine, lies at the point of relatively little olivine, and that most rocks contain more olivine than the individualization boundary mentioned. But if less olivine is present the solidification commences with the crystallization of one of the other minerals. Returning to the rocks which consist only or nearly only of olivine

¹ As early as in my first mineral-synthetic work ("Studies on Slags," 1885) I opposed this misconception, which *inter alia* also has been expressed in petrographical works of later years. But when a misconception of an authoritative character has been impressed on one's consciousness, it may require a decade of years to uproot it.

and (basic) plagioclase, it has already been indicated by A. Harker^x that of these two minerals, the one present in quantity above a certain limit first commences crystallizing. This is also in accordance with my own investigations.

I find it superfluous to discuss the plagioclase rocks with considerable olivine, and as a consequence with crystallization of an

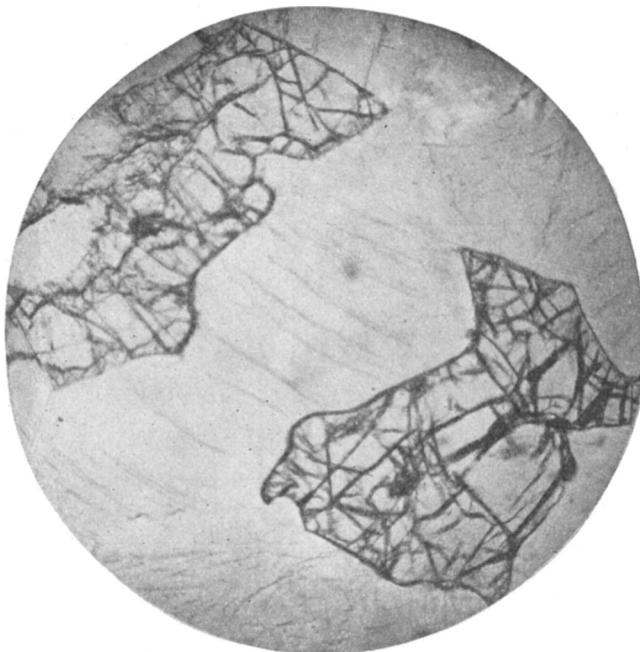


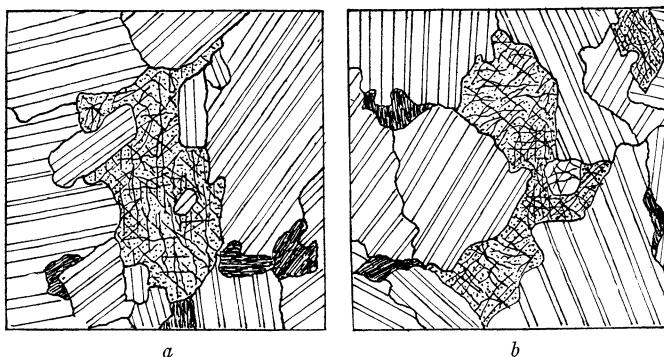
FIG. 23.—Photomicrograph (20:1)

essential part of the olivine before the commencement of the solidification of the plagioclase. But I am going to discuss the inverse proportion, much plagioclase and little olivine, and choose as an example an olivine-bearing labradorite rock from the Ekersund field. This consists of nearly 90 per cent labradorite (Ab_1An_1), about 7 per cent olivine (optically negative; $2V = ca. 85^\circ$, consequently with about $0.25\ Fe_2SiO_4:0.75\ Mg_2SiO_4$), besides a little diallage. (See photograph Fig. 23 and drawing Fig. 24.)

^x *The Natural History of Igneous Rocks*, 1909, p. 170.

The olivine here shows no sign of idiomorphism, but this is often the case with labradorite. Laths (parallel to 010) of the latter here and there (Fig. 24a) protrude into the olivine, and the straight-edged boundary which we often observe (Fig. 23) between the labradorite and the olivine is not caused by the crystal-limit of the olivine, but by that of the plagioclase. The feldspar must thus here have commenced crystallizing at an earlier stage than the olivine, which, in the same manner as the diallage in Figures 24a and 24b, and as the hypersthene in Figure 14, chiefly forms an intervening mass between relatively large labradorite individuals.

In the *olivine-rich olivine hyperites* (hyperitic-structured olivine gabbros) with about 25–30 per cent olivine, 60 per cent



FIGS. 24a and 24b.—Drawings (20:1)

Anorthosite from Ekersund, Norway, containing *ca.* 90 per cent labradorite ($\text{Ab}_1\text{An}_{11}$), *ca.* 7 per cent olivine (dotted in Fig. 24), and a little diallage (dark shading in Fig. 24, not seen in the photograph). The straight lines in Figure 23 represent the idiomorphic contours of the labradorite against the olivine.

labradorite, 10–20 per cent diallage, and a little magnetite, etc., the olivine chiefly appears in synneutic individuals with very good idiomorphism against the diallage and partial idiomorphism also against the plagioclase (see, for instance, Fig. 33). Considering only the silicate minerals, we find consequently that first a good deal of olivine solidified, then the labradorite, and at a later stage the diallage also commenced crystallizing.

In the *olivine-poor olivine hyperites*, with only 5–10 per cent olivine, we find, on the other hand, in the relation between the olivine and the labradorite quite a different structural phenome-

non, *viz.*, lath-shaped labradorite individuals protruding into the olivine, and the latter shows no sign of idiomorphism even against the labradorite. The olivine chiefly fills the intervening spaces between the plagioclase laths in the same manner as in the anorthosite illustrated in Figures 23 and 24. We refer, for instance, to Figures 48 and 49 where the original structure, however, is partly effaced by the here quite strongly developed reaction rims between the olivine and the labradorite. In these olivine-poor olivine hyperites a greater or lesser part of the plagioclase must according to the structure have crystallized earlier than the olivine.

On the basis of the crystallization sequence we draw the conclusion that the individualization boundary at high pressure between the olivine (about $1\text{Fe}_2\text{SiO}_4\text{.}2\text{Mg}_2\text{SiO}_4$) and basic plagioclase lies at little olivine and much plagioclase. As an estimate we may set the individualization boundary (by weight) at 0.15 Oliv.:0.85 Ab₁An₁, 0.25 Oliv.:0.75 Ab₁An₃, and probably about 0.35 Oliv.:0.65 An. That these statements are approximately right is verified by a study of the "orbicular gabbro" from Debessa, California, described by A. C. Lawson,¹ which carries orbs with changing shells (challotes) of radially arranged olivine together with bytownite. This structure must depend on a *simultaneous* crystallization of the two minerals, that is to say, a crystallization along a eutectic boundary-line. From the quantitative analysis we calculate the composition of this boundary at about 0.34 Oliv. (0.35 Fe₂SiO₄, 0.65 Mg₂SiO₄):0.66 Plag. (Ab₁₆An₈₄, consequently about Ab₁An₅.)

The quartary system Ab:An:Mg₂SiO₄:Fe₂SiO₄ separates at high pressure into two individualization fields, *viz.*, Ab+An and Mg₂SiO₄+Fe₂SiO₄. We may here apply the same general considerations as for the system Ab+An and CaMgSi₂O₆+CaFeSi₂O₆ (see p. 442).

OLIVINE AND PYROXENE

Olivine and monoclinic pyroxene.—Forsterite, Mg₂SiO₄ (melting-point=1890°) and diopside, CaMgSi₂O₆ (melting-point=1391°), form, according to N. L. Bowen,² a eutectic, 88 per cent diopside: 12 per cent forsterite with melting-point=1386°, consequently

¹ *Univ. of Cal. Publications, Dept. of Geol.*, Vol. III (1904).

² "The Ternary System Diopside-Forsterite-Silica," *Amer. Jour. of Sci.*, Vol. XXXVIII (1914).

only 4–5° below the melting-point of diopside. According to my earlier studies on slags, the individualization boundary between augite ($\text{CaMgSi}_2\text{O}_6$ with some $\text{CaFeSi}_2\text{O}_6$, $\text{MgAl}_2\text{SiO}_6$, etc.) and olivine (Mg_2SiO_4 with some Fe_2SiO_4 and Mn_2SiO_4 , consequently with a much lower melting-point than pure Mg_2SiO_4) lies at about 70 per cent of augite: 30 per cent of olivine. At this individualization boundary a decrease of the melting-point appears according to experimental investigations.¹ We accordingly here have to deal with a eutectic boundary-line between the two mix-crystals. The location of this boundary is chiefly dependent upon the composition of the olivine, and this is probably due to the fact that the melting-point interval of the olivine is considerably lowered by some Fe_2SiO_4 . (See Fig. 22.)

Regarding $\text{Mg}_2\text{SiO}_4:\text{MgSiO}_3$, and especially with regard to the dissociation of MgSiO_3 at the pressure of one atmosphere and at high temperature (1577–1555°), some forsterite first being solidified from melted MgSiO_3 , we refer to Bowen's investigations which are discussed in a following chapter. I here arrive at the result that the dissociation of MgSiO_3 , determined at the pressure of one atmosphere, cannot be transferred to apply to (Mg, Fe) SiO_3 or (Mg, Fe) SiO_3 at *high* pressure.

In igneous rocks consisting of olivine and orthorhombic or monoclinic pyroxene, the olivine chiefly appears in idiomorphic individuals when the olivine forms at least one-third, and the pyroxene at most two-thirds. This fact is so well known that I find it superfluous to give special examples. But when the olivine is present only in small quantity, the sequence of crystallization is quite turned about. Such rocks, with predominant pyroxene and quite little olivine, are in themselves rare, and furthermore the olivine in these rare rocks is only exceptionally fresh enough to permit a detailed study of the original structure of the rock. As far as I know, these rocks have not previously attracted any special attention; I shall therefore discuss a couple of examples.

In a hypersthene-norite from Nonaas-Litland in Hosanger, Norway (see analysis in the chapter on norites in Part II), a con-

¹ See "Silikätschmelzlös.," II.

cretion of an *olivine-bearing hypersthene* (or olivine-augite-hornblende-hypersthene) appears locally (at Nonaas), with a chemical composition:

about	47-48 per cent SiO ₂
about	0.5-1 per cent TiO ₂
about	5-6 per cent Al ₂ O ₃
about	2.5-3 per cent Fe ₂ O ₃
about	12-13 per cent FeO
about	17-18 per cent MgO
about	11-12 per cent CaO
about	0.5-1 per cent alkali

This rock, which is quite fresh, consists mineralogically of about 75 per cent pyroxene, viz., about 50 per cent hypersthene (optically negative, $2V = ca. 80^\circ$, that is to say, with stoichiometric 25-30, closest at about 27 per cent $FeSiO_3$) and about 25 per cent monoclinic pyroxene (extinction-angle $39-40^\circ$); on an average about 12 per cent olivine (optically negative, $2V = ca. 83^\circ$, consequently with stoichiometric¹ about 30 per cent Fe_2SiO_4); about 12 per cent intensively greenish-brown, primary hornblende; and in addition locally 0.5 per cent biotite and about 0.5 per cent plagioclase, the latter only here and there as mesostasis of quite subordinate importance. Oxidic iron ore is entirely lacking. Apatite and pyrites appear in small quantity. On the photomicrograph, Figure 25, the light-streaked mineral chiefly consists of hypersthene and a few individuals of monoclinic pyroxene. Uppermost to the right we see a hypersthene individual, cut at right angle to the *c*-axis.

The mineral which on account of the strong absorption of light shows dark-gray in the photograph is hornblende, and the mineral which appears white is olivine, quite fresh, without any sign of serpentinization or other change. The pyroxene individuals show, as well in length as in cross-section, quite good idiomorphism against the olivine. The same, though not quite so distinctly, is the case with the hornblende, which belongs to a somewhat later stage of crystallization than the hypersthene (see above). On the other hand, the olivine does not show even a sign of idiomorphism against the hypersthene and the other minerals, but forms—in

¹ The optical determinations have been undertaken by Docent Carstens and myself in collaboration.

the same manner as the plagioclase in the gabbro rocks which are especially rich in hypersthene or diallage—a mass of putty or a *Zwischenklemmungsmasse* (mesostasis) between the ferromagnesian silicate minerals.

So we arrive at the result that in the rock in question, with little olivine and predominant hypersthene, with monoclinic pyroxene and some hornblende, the olivine belongs to the *last* stage of crystallization.



FIG. 25.—Photomicrograph (24:1) of olivine-bearing hypersthene with some diallage and hornblende, from Nonaas, Hosanger, Norway. The light-gray mineral is hypersthene with some diallage, the dark-gray is hornblende, and the white olivine.

Also in some other olivine-bearing pyroxenites, moderately rich in iron, with predominant hypersthene, or diallage or both, and in addition with only a quite small amount, say 10 or 15 per cent, of olivine, the structure proves the late commencement of the crystallization of the olivine.

If we pass on to the dunites and saxonites *poor in iron*, usually with 40-43 per cent SiO_2 , 42-48 MgO , 7-10 FeO , 0-1.5 CaO , and

a little Al_2O_3 , we find that the dunites consist nearly exclusively of olivine, and the saxonites usually of predominant olivine with only quite little bronzite or enstatite-bronzite.

Olivine-bronzite (or enstatite) rocks with predominant orthopyroxene and quite little olivine are very rare, and personally I have only once (1893) found such a rock, viz., as a local facies of a peridotite at Esjeholmen near Næsö, in the Hestmandö district, near the Polar Circle in the northern part of Norway.¹

As illustrated in Figure 26, there here appear rosettes of radially arranged bars of enstatite which in most places are entirely unchanged, but in some places somewhat altered to tremolite, clino-chlorite, talc, and magnesite.

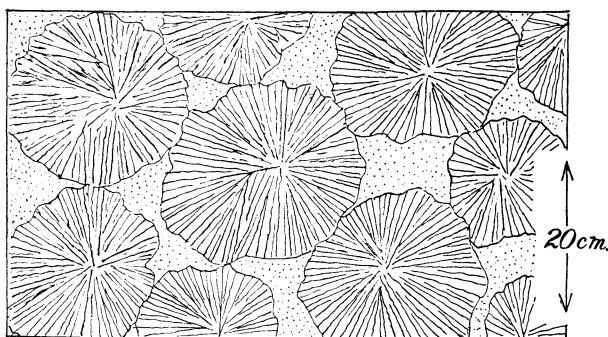


FIG. 26.—Enstatite-olivine rock from Esjeholmen, near Næsö, Hestmandö district, northern Norway. Contains great rosettes of enstatite and an intervening mass of olivine with some enstatite. (1/10 nat. size.)

The bars of enstatite in these rosettes may reach a length of 1 dm., or somewhat more, and the enstatite rosettes may have the size of the head of a full-grown man. The intervening mass between the enstatite rosettes consists of olivine and enstatite. In the entire rock we may reckon about 80 per cent enstatite rosettes and only about 20 per cent intervening mass, consequently for the whole rock about 90 per cent enstatite and 10 per cent olivine, in addition to a minimal quantity of chromite. I cannot explain this structure otherwise than that at first the enstatite of the large rosettes was formed, and later the intervening mass, consisting of olivine and enstatite. The result of this is that the sequence of

¹ See a treatise by myself in *Zeitschr. f. prakt. Geol.*, 1894, pp. 389-92, and a treatise by C. W. Carstens, "Norske peridotiter," I, *Norsk geol. tidskr.*, Vol. V (1918).

crystallization in the deep-seated rocks of olivine and monoclinic, or orthorhombic, pyroxene must be explained by the same laws as for the other ordinary rock-forming minerals, and that the individualization boundary lies at predominant pyroxene:little olivine.

ON THE RELATION BETWEEN MgO AND FeO (OR BETWEEN
Mg-SILICATE AND Fe-SILICATE) IN THE FERROMAGNESIAN
SILICATES, CRYSTALLIZED FROM THE SAME MAGMA

We include a selection of analyses of the primary ferromagnesian minerals appearing in the same rock:

	No.	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	H ₂ O	Total
Websterite (No. 49) with Bronzite (b) and Diopside (c)															
Websterite.....	49	52.55	0.14	0.44	2.71	1.27	4.90	0.24	20.30	16.52	0.27	Tr.	1.00	100.52	
Bronzite.....	b	54.53	.....	0.30	1.93	1.70	8.92	0.28	20.51	2.25	.....	.....	1.12	100.56
Diopside.....	c	51.80	0.13	0.51	2.21	1.29	3.50	Tr.	17.76	20.99	.....	.....	0.65	98.84
Pikrite (No. 50) with Bronzite (b) and Diopside (c)															
Pikrite.....	50	37.12	0.40	4.96	8.92	7.62	0.40	26.92	6.14	0.40	0.49	0.10	5.04	98.60
Bronzite.....	b	54.20	.....	0.29	2.05	.....	10.08	.....	29.00	2.49	.....	.....	0.42	98.53
Diopside.....	c	52.63	.....	0.72	2.24	.....	6.84	.....	17.30	20.04	.....	.....	0.57	100.34
Hypersthene Diabase (No. 51) with Hypersthene (b) and Augite (c)															
Diabase.....	51	50.86	7.95	7.41	18.93	13.29	1.34	0.20	100.00
Hypersthene.....	b	52.16	3.00	0.43	15.16	0.36	21.80	5.94	0.16	0.04	0.08	99.24
Augite.....	c	49.33	9.15	0.27	9.05	14.58	16.36	0.55	0.10	0.25	99.73
Diallage-Hornblende-Gabbro (No. 52) with Diallage (e) and Brown, Primary Hornblende (d)															
Gabbro.....	52	53.19	0.25	11.42	1.74	8.15	0.17	10.84	11.01	2.97	0.31	100.05
Diallage.....	e	51.23	0.86	.....	2.75	3.88	14.09	Tr.	17.05	0.74	.....	.....	1.75	101.35
Hornblende.....	d	48.04	8.98	16.44	18.87	6.72	99.06
Dacite (No. 53) with Hypersthene (b), Biotite (e), and Ilmenite (f)															
Dacite.....	53	63.27	1.30	16.50	0.68	5.10	0.03	2.48	4.18	2.36	2.68	0.15	0.61	99.50
Hypersthene.....	b	50.42	3.51	4.06	2.10	23.54	0.24	13.04	1.30	Tr.	0.69	0.92	0.16	99.98
Biotite.....	e	39.86	7.95	11.13	1.39	18.10	0.58	9.88	Tr.	0.35	6.73	3.63	99.60
Ilmenite.....	f	67.28	31.92	0.80	100.00
Peridotite (No. 54, Kimberlite, Strongly Decomposed) with Olivine (g), Garnet (h), and Ilmenite (f)															
Peridotite.....	54	29.81	2.20	0.43	2.01	5.16	4.35	0.23	32.41	7.69	0.11	0.20	0.35	8.92	100.86
Olivine.....	g	40.04	0.07	0.24	0.39	2.36	7.14	0.20	40.68	1.16	0.08	0.21	0.04	0.86	99.42
Garnet.....	h	41.32	0.16	0.01	21.21	4.21	7.93	0.34	10.32	4.94	0.07	.....	0.17	100.58
Ilmenite.....	f	0.76	49.32	0.74	2.84	9.13	27.81	0.20	8.68	0.23	0.19	.....	0.20	100.00

No. 49: Websterite, composed only of bronzite and diallage. Hebbville near Baltimore. G. H. Williams, *Amer. Geologist*, Vol. VI; F. W. Clarke, *U.S. Geol. Sur. Bull.* 228 (1904), p. 51.—No. 50: Pikrite. Schwarzenstein, Fichtelgebirge. In the rock 0.09 per cent CO₂. Gümbel, *Geogr. Beschreibung Bayerns*, 1879. (Rosenbusch, *Gesteinslehre*, p. 352.)—No. 51: Hypersthene diabase. Twins by Rapidan, Virginia. Campbell and Brown, *Bull. Geol. Soc. Am.*, II.—No. 52: Diallage-hornblende-gabbro. Veltein, in the Alps. Küchler, *Chemie der Erde*, I, 1914. The analysis of the rock from Hecker, *Neues Jahrb. f. Min., Geol. u. Pal.*, Beil., Bd. XVII (1903).—No. 53: Hypersthene-biotite-dacite. Upway, Victoria. Skeats, *Quart. Jour. Geol. Soc. London*, 1910. In the rock 0.16 per cent S. In the biotite H₂O+, 3.20 and H₂O÷, 0.43 per cent.—No. 54: Kimberlite, strongly decomposed. From Elliot County, Kentucky. In the rock 8.92 per cent H₂O, 6.66 CO₂, 0.28 SO₃, 0.05 NiO. Diller, *U.S. Geol. Soc. Bull.* 38, and *Amer. Jour. Sci.*, 3d Series, Vol. XXXII; Clarke, *U.S. Geol. Soc. Bull.* 228, p. 66.

OLIVINE AND ORTHORHOMBIC PYROXENE

We shall commence with some analyses of olivine and bronzite from olivine nodules in basalts. We shall base the calculations for the bronzite, often somewhat decomposed, on the entire quantity of iron found analytically. In reality a little, but only very little, iron in the bronzite will appear as Fe₂O₃.

The stoichiometric relation between MgO and FeO in olivine and bronzite for olivine nodules:

Styria (Kappenstein, etc.)	{	55a	Olivine	1 MgO:0.11 FeO
		55b	Bronzite	1 MgO:0.14 FeO
		56a	Olivine	1 MgO:0.11 FeO
		56b	Bronzite	1 MgO:0.10 FeO
		57a	Olivine	1 MgO:0.09 FeO
Dreizer Weiher, Eifel	{	57b	Bronzite	1 MgO:0.11 FeO
		58a	Olivine	1 MgO:0.11 FeO
		58b	Bronzite	1 MgO:0.10 FeO
Stempel, Marburg	{	59a	Olivine	1 MgO:0.10 FeO
		59b	Bronzite	1 MgO:0.11 FeO
Kaiserstuhl, Baden	{	60a	Olivine	1 MgO:0.09 FeO
		60b	Bronzite	1 MgO:0.10 FeO
Reihenweiler, Alsace	{	61a	Olivine	1 MgO:0.14 FeO
		61b	Bronzite	1 MgO:0.14 FeO

Nos. 55a, b, and c: Kukurzenkezel near Kappenstein: Schadler, *Tscherm. Mitt.*, Vol. XXXII (1914).—No. 56a and b: Schiller, Becke, *Tscherm. Mitt.*, Vol. XXIV.—Nos. 57a and b: Th. Kierulf, *Bischof's chem. Geol.*, and *Pogg.*

Ann., Vol. CXLI.—Nos. 58a, b, and c: Philipp, *Neues Jahrb. f. Min.*, etc., 1871, and Rammelsberg, *Pogg. Ann.*, Vol. CXLI.—Nos. 59a, b, and c: Bauer, *Neues Jahrb. f. Min.*, etc., 1891, II.—Nos. 60a and b: Knop, *Neues Jahrb. f. Min.*, etc., 1877.—Nos. 61a and b: Linck, *Zeitschr. f. Kryst. u. Min.*, Vol. XVIII.

The value of FeO in the bronzite should be reduced a little throughout, probably about one-tenth in most cases.

Joh. Schiller has discussed the question in hand in a special treatise,¹ partly on the basis of several of the analyses here given of olivine nodules in basalts, and partly on the determination of the chemical composition of the two minerals on the basis of the axial angle and optical character. He comes to the result that MgO and FeO in the feldspar-free rocks are quite evenly distributed in the olivine and orthorhombic pyroxene, and this conclusion is confirmed by my own investigations. But with regard to the rocks containing feldspar he supposes a relative, sometimes even a relatively extensive, enrichment of MgO in the olivine. The observations on which he bases this last construction, however, are few, and in my opinion rather dubious.²

Olivine and orthopyroxene,³ isolated from a series of peridotites poor in iron (saxonites, olivine-schists, etc.) with only very little Al_2O_3 , Fe_2O_3 , and CaO , show:

Olivine, 1 MgO:0.08, 0.08, 0.08, 0.10, 0.11 FeO;

Orthopyroxene, 1 MgO:0.07, 0.07, 0.07, 0.10, 0.12, 0.12, FeO.

In peridotites, a little richer in iron, and at the same time carrying somewhat more Al_2O_3 , Fe_2O_3 , and CaO , we find:

Olivine, 1 MgO:0.15, 0.21 FeO;

Orthopyroxene, 1 MgO:0.13, 0.15, 0.16 FeO.

As well with regard to the short report above as to Schiller's investigations, MgO and FeO in the feldspar-free rocks in question are quite evenly divided between the two minerals. The various lesser differences—which would indicate a small relative enrichment

¹ *Tscherm. Mitt.*, Vol. XXIV (1905).

² Especially for the extremely low FeO-contents in olivine from an olivine-gabbro from Tilai, Ural.

³ Enstatite-bronzite-hypersthene deserves, in the same manner as anorthite-bytownite-labradorite-andesine-oligoclase-albite, a common term, and as such I will use "orthopyroxene," that is to say, pyroxene belonging to the orthorhombic system. I believe I occasionally have heard or read this term before, so the proposition is not originally mine.

of MgO in the olivine in some cases, and in the orthopyroxene in others—approximately balance, and probably depend chiefly on the source of errors connected with the determinations.

If we pass on to the *gabbroic* rocks, we find that hypersthene, in the common anchi-eutectic norites, usually shows—as well on the basis of the analysis of isolated hypersthene, as by the determinations of the axial angle undertaken by earlier investigators and by myself—a composition between about 30 and 38–40 per cent FeSiO₃ (stoichiometric). And the olivine shows, as well on the basis of the analyses of isolated material, as on my own determinations of the axial angle, about 32–35 per cent Fe₂SiO₄.

In the hypersthenite-norites (with only relatively little plagioclase) we usually find, however, a relatively lower percentage of iron, as well in the rock as in the separated silicate minerals. This is discussed more elaborately in Part II. We shall include a couple of separate determinations: The thin secretion of a hypersthenite-norite, above mentioned (Fig. 25), consisting chiefly of hypersthene, augite, hornblende, and olivine shows:

Hypersthene, optically negative, $2V = ca. 80^\circ$, gives 25–30 (about 27) per cent FeSiO₃;

Olivine, optically negative, $2V = ca. 83^\circ$, gives about 30 per cent Fe₂SiO₄.

Olivine-carrying norite with only about 40 per cent labradorite from Skjækerdalen (Figs. 20–21):

Hypersthene, optically negative, $2V = ca. 80-85^\circ$, gives about 25 per cent FeSiO₃;

Olivine, optically negative, $2V = ca. 85-88^\circ$, gives 20–25 per cent Fe₂SiO₄.

Also in the igneous rocks containing feldspar, we find approximately the same MgO:FeO proportion in both minerals. Any relative enrichment of MgO in the olivine is usually not to be found.

ORTORHOMBIC AND MONOCLINIC PYROXENE

As special Fe₂O₃ determinations are lacking in several cases and in others are little instructive on account of a later oxidation, we in both minerals originate from the entire percentage of iron, this giving a quite true image of the relative proportions of MgO and FeO in the two minerals. On account of the small percentage of Fe₂O₃ the statements for FeO ought, however, for the

orthorhombic pyroxene to be reduced about one-tenth, and for the monoclinic pyroxene, which throughout contains a little more Fe_2O_3 , about one-eighth. This correction, however, is of small extent.

The stoichiometric proportion between MgO and FeO in orthorhombic and monoclinic pyroxene from the same rock:

Olivine nodules from basalts...	Marburg	$\begin{cases} 59b \\ 59c \end{cases}$	Bronzite	$\text{r MgO}:0.11 \text{ FeO}$
	Dreizer		Diopside	$\text{r MgO}:0.07 \text{ FeO}$
	Weiher	$\begin{cases} 58b \\ 58c \end{cases}$	Bronzite	$\text{r MgO}:0.11 \text{ FeO}$
			Diopside	$\text{r MgO}:0.14 \text{ FeO}$
	Kaiserstuhl	$\begin{cases} 60b \\ 60c \end{cases}$	Bronzite	$\text{r MgO}:0.10 \text{ FeO}$
			Diopside	$\text{r MgO}:0.16 \text{ FeO}$
	Kappenstein	$\begin{cases} 55b \\ 55c \end{cases}$	Bronzite	$\text{r MgO}:0.14 \text{ FeO}$
			Diopside	$\text{r MgO}:0.18 \text{ FeO}$
	Websterite	$\begin{cases} 49b \\ 49c \end{cases}$	Bronzite	$\text{r MgO}:0.20 \text{ FeO}$
			Diopside	$\text{r MgO}:0.15 \text{ FeO}$
Pikrite		$\begin{cases} 50b \\ 50c \end{cases}$	Bronzite	$\text{r MgO}:0.20 \text{ FeO}$
			Diopside	$\text{r MgO}:0.22 \text{ FeO}$
Hypersthene Diabase		$\begin{cases} 51b \\ 51c \end{cases}$	Hypersthene	$\text{r MgO}:0.40 \text{ FeO}$
			Augite	$\text{r MgO}:0.35 \text{ FeO}$

If we deduct the small, analytically found figures for Fe_2O_3 from the last rock (No. 51), we have:

Hypersthene, No. 51b, $\text{r MgO}:0.39 \text{ FeO}$;

Augite, No. 51c, $\text{r MgO}:0.35 \text{ FeO}$.

The seven double analyses of orthorhombic and monoclinic pyroxene give approximately the same proportions between MgO and FeO , in some cases a little difference in one, and in some in the other direction, but there is no particularly constant enrichment of one component in either of the two minerals. A series of analyses shows that where orthorhombic and monoclinic pyroxene appear as primary formations in the same rock, the monoclinic is characterized by a somewhat higher percentage of TiO_2 , Cr_2O_3 , Al_2O_3 —and probably also of Fe_2O_3 —than the orthorhombic.

DIALLAGE AND PRIMARY BROWN HORNBLENDE

Küchler's two analyses from a diallage-hornblende gabbro (No. 52) show, the total quantity of iron being reckoned as FeO :

Diallage, No. 52c, $\text{r MgO}:0.57 \text{ FeO}$;

Hornblende, No. 52d, $\text{r MgO}:0.48 \text{ FeO}$.

If we deduct 3.88 per cent Fe_2O_3 in the diallage and, at an estimate, 2.0 per cent Fe_2O_3 in the hornblende, we get:

Diallage, No. 52c, 1 MgO : 0.46 FeO ;
Hornblende, No. 52d, 1 MgO : 0.42 FeO ,

consequently, as emphasized by Küchler, about the same MgO : FeO proportion in both minerals.

HYPERSTHENE AND BIOTITE

The two analyses from a dacite (No. 53) show:

Hypersthene, No. 53b, 1 MgO : 1.00 FeO ;
Biotite, No. 53e, 1 MgO : 1.02 FeO ,

consequently exactly the same MgO : FeO proportion in both minerals.

If for the Romsaas quartz-orbicular-norite, which in the entire rock only contains about 0.5 per cent Fe_2O_3 , we assume as an estimate 1 per cent Fe_2O_3 in the biotite, we get:

Hypersthene, No. 41, 1 MgO : 0.39 FeO ;
Biotite, No. 42, 1 MgO : 0.27 FeO .

Even if the last figure is not quite exact, relatively somewhat less FeO appears in the biotite than in the hypersthene.

When there is a simultaneous appearance of biotite and hypersthene in the same rock, the biotite seems throughout to carry considerably more TiO_2 than the hypersthene.

The summary, here briefly stated, verifies the earlier conclusion, especially by A. Merian¹ (1884), W. Wahl² (1906), and Küchler (*loc. cit.*, 1914), viz., that the composition of the ferromagnesian silicates depends quite simply upon the composition of the entire rock or magma, and further that the relations between MgO and FeO (or Mg-and Fe-silicate) in two from the same magma crystallizing ferromagnesian silicates such as olivine:orthorhombic

¹ "Analysen gesteinsbildender Pyroxene," *Neues Jahrb. f. Min.*, etc., Bd. III (1884).

² *Die Enstatitaugite* (dissertation), Helsingfors, 1906; *Tscherm. Mitt.*, Vol. XXVI (1907).

pyroxene, orthorhombic:monoclinic pyroxene, diallage:primary hornblende, hypersthene:biotite, are not subject to extensive variations. We may find a little variation sometimes in one and sometimes in the other direction, but this may be due in part to inaccurate determinations. But all in all, we here have approximately the same $MgO:FeO$ proportions in both minerals. We especially emphasize that no mineral is characterized by a constant relative enrichment either of MgO or FeO . Lesser variations, with regard to the $MgO:FeO$ proportion, by two or still more ferromagnesian silicates, crystallizing from the same magma, may be due to a series of factors, of which we may mention the horizontal distance between the liquidus and solidus curves (or the difference between the a:b proportion in the first crystallized mix-crystal and in the liquid phase); the degree of equilibrium between the solid and liquid phases; the electrolytic dissociation.

A *small* horizontal difference between the liquidus and solidus curves, and a nearly complete equilibrium between the solid and liquid phases will cause nearly the same $MgO:FeO$ proportion between the segregated ferromagnesian silicates and the magma, and consequently also between the ferromagnesian silicates mutually.

As well in olivine as in orthopyroxene and diopside-hedenbergite, the Mg -silicate is concentrated in the first mix-crystal. By more or less incomplete equilibrium between the liquid and solid phases—as in the dike and effusive rocks—we may expect a relative enrichment of MgO in the mineral which first commenced crystallizing. With two ferromagnesian silicates we may generally expect a more evenly distributed $MgO:FeO$ proportion among deep-seated rocks with complete or nearly complete equilibrium between liquid and solid phases than among dike and effusive rocks.

Addition.—Also in *ilmenite* a little MgO enters, *viz.*, as $MgTiO_3$. In this manner ilmenite No. 54f from a peridotite (with about 0.12 FeO :0.88 MgO in the entire rock) shows not less than 8.68 per cent MgO , or 0.64 FeO :0.36 MgO . The ilmenite from the labradorite rock near Ekersund (with about 0.5 FeO :0.5 MgO

in the entire rock) usually contains 3 to 4, up to 5.14 per cent MgO (the last analysis equivalent to 0.78 FeO:0.22 MgO). In the dacite No. 53, with 0.53 FeO:0.47 MgO in the whole rock, the hypersthene as well as the biotite carries almost exactly 0.50 FeO:0.50 MgO and the ilmenite 0.96 FeO:0.04 MgO.

The proportions of FeO and MgO in the ilmenite, from observation of the three rocks just mentioned, must be a function of the FeO:MgO proportion in the entire rock or in the original magma, but in such a manner that the ilmenite throughout shows a very extensive relative enrichment of FeO (as FeTiO_3) and consequently vice versa an extensive, relative decrease of MgO (as MgTiO_3).

[To be continued]